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Second Metacarpal Midshaft Geometry in an Historic Cemetery Sample

RICHARD A. LAZENBY*
Anthropology Program, University of Northern British Columbia, Prince George, British Columbia, Canada

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ABSTRACT Study of bone mass at the second metacarpal midshaft has contributed to our understanding of skeletal growth and aging within and between populations and has relied extensively on noninvasive techniques and in particular radiogrammetric data. This study reports age, sex, and side variation in size and shape data acquired from direct measurement of cross-sections obtained from a large (n = 356), homogeneous skeletal sample. Correlation analysis and three-way ANOVA of size-adjusted data confirm general impressions of patterned variation in this element: males have absolutely but not necessarily relatively larger bones than females; the right side is larger than the left, though a larger than expected proportion (approximately 25%) of left metacarpals exhibits greater values than the right; and bone mass but not strength (in males) declines with age. Contrary to the widely accepted assumption of circularity for this location, direct measurement of cross-sectional geometry confirms previous biplanar radiogrammetric conclusions regarding the noncircularity of the second metacarpal midshaft and identifies a significant difference between males and females, with the latter having a more cylindrical diaphysis. Deviation of the axes of maximum and minimum bending strength associated with noncircularity suggests a distribution of bone mass to resist bending moments perpendicular to the distal palmar arch, though this conclusion awaits more robust study of the functional anatomy of the metacarpal diaphysis. Am J Phys Anthropol 106:157–167, 1998.

The study of bone size and shape can inform researchers of patterns of adaptation vis-à-vis diet, activity, health, and other life history parameters within and between past and present human populations. The second metacarpal has been one of a few skeletal elements favoured for such study. As a short, robust tubular bone, it has a propensity for preservation in archaeological samples, and as an element of the peripheral axial skeleton it facilitates radiographic investigation in living populations. From an anthropological perspective, the second metacarpal has contributed to our understanding of skeletal growth, development, and aging in both healthy and nutritionally compromised populations (Garn, 1970; Garn et al., 1968, 1972, 1992; Himes and Malina, 1977; Himes and Huang, 1993; Kusec et al., 1988; Plato et al., 1982, 1984a; Smithgall et al., 1966). Similarly, appreciation of population variation in skeletal asymmetry, strength, and lateral hand dominance owes much to bone mass data from the second metacarpal (De-

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*Correspondence to: Richard A. Lazenby, Anthropology Program, University of Northern British Columbia, Prince George, British Columbia, Canada V2N 4Z9. E-mail: lazenby@unbc.ca

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queker and van Tendeloo, 1982; Garn et al., 1976), with particular emphasis on studies originating from the Baltimore Longitudinal Study on Aging (BLSA) (Fox et al., 1986, 1995; Plato and Norris, 1980; Plato and Purifoy, 1982; Plato et al., 1980, 1984b; Roy et al., 1994). The second metacarpal has also contributed to methodology in forensic anthropology with regard to stature estimation (Meadows and Jantz, 1992) and sex identification (Falsetti, 1995; Scheuer and Elkington, 1993).

Clinical studies have also placed considerable emphasis on examination of the second metacarpal, including retrospective investigation of population differences in sex- and cohort-specific rates of bone gain and loss (Aguado et al., 1997; Guesens et al., 1986; Maggio et al., 1995, 1997; Rico et al., 1994; van Hemert et al., 1990) screening for fracture prevalence and risk assessment, beginning with the classic early studies of Barnett and Nordin (1960), and more recently applying increasingly sophisticated methods such as automated photodensitometry (Derisquebourg et al., 1994; Fukunaga et al., 1990; Meema and Meindok, 1992; Wishart et al., 1993). Other applications include drug intervention evaluation (Nordin et al., 1985) and investigating the impact of dietary disorders such as anorexia nervosa on skeletal health (Passloff et al., 1992).

The majority of studies in both the anthropological and clinical realms have relied upon quantitative analysis of hand-wrist radiographs which, for the purpose of bone mass measurement, provide an effectively one-dimensional view of the medial and lateral metacarpal cortices. Such images are limited as a source of data regarding bone mass, as they permit direct measurement of relatively few parameters, including length, total width (TW), medullary width (MW), and medial and lateral cortical thickness (the last four invariably taken at midshaft). Derived variables and indices are often calculated, including combined cortical thickness (CCT) and percent cortical area (PCA) ($PCA = TW^2 - MW^2/TW^2 * 100$), the latter in particular serving as a proxy measure for bone volume (Garn, 1970). Indices such as PCA make assumptions about the shape of the metacarpal midshaft which appear to be unwarranted (Lazenby, 1995) and which lead to biased estimates of mass (Lazenby, 1997). A companion paper in preparation explores the significance of such biases for interpreting metacarpal radiogrammetric data, while the purpose of this submission is to report normative data for size and shape variation in the adult second metacarpal midshaft obtained from direct, invasive measurement of bones recovered from a a large, homogeneous archaeological sample. These data permit testing of three null hypotheses which have been the focus of much previous research, specifically that parameters of geometric variation 1) do not vary by sex (male = female) 2) do not vary by side (left = right) and 3) do not vary by age (young adult = middle adult = old adult).

MATERIALS AND METHODS

Sample

Data for this study were obtained from 356 unilateral (n = 40) or paired (n = 316) adult second metacarpals from the nineteenth-century St. Thomas's Anglican Church cemetery, Belleville, Ontario. The cemetery was active between 1821 and 1874. A total of 198 individuals are represented (116 males and 82 females), ranging in age from 17–88 years (mean ± SD: males = 46.1 ± 13.9 years; females = 42.3 ± 14.0 years; t = 1.92, ns). Of these, 40 are historically known with documented age and sex. Individuals interred in the cemetery are primarily Caucasian and originated in western Europe, with the majority from the British Isles (Saunders et al., 1992). Characteristics of site topography and soil structure contributed to exceptional preservation of this sample (Saunders et al., 1995) and facilitated age estimation for the unknown individuals based on pubic symphseal and auricular surface morphology and sex determination from pelvic morphology. Saunders et al. (1992, for age) and Rogers and Saunders (1994, for sex) found good approximation in tests of these methods against the documented subsample, though older adults tended to be somewhat underaged. While interval age values were derived from averaging estimates from the different techniques, this study treats age ordinally, as young adult (≤35 years); middle adult (36–50

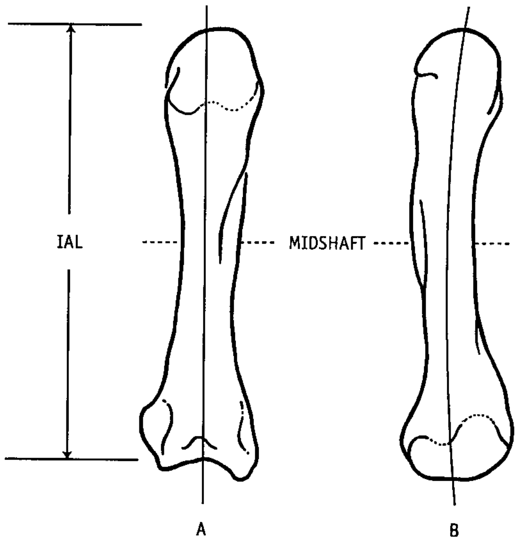

Fig. 1. Dorsal and medial views of the second metacarpal showing location of the dorsopalmar (A) and mediolateral (B) anatomical axes. The DP axis is defined by a line extending from the basal notch for articulation with the trapezoid and bisecting the distal expansion accommodating the metacarpal head. The ML axis is defined by an arc extending from the conjunction of the articular facets for the capitate and base of the third metacarpal proximally to the midpoint of the head distally. IAL, interarticular length.

years), and old adult (≥51 years), combining both the known and unknown subsamples.

Data

Several geometric parameters indicative of cross-sectional size, functional adaptation, and skeletal aging (e.g., Ruff, 1992) were measured directly from approximately 200 micron thick sections obtained from the metacarpal midshaft, defined as one-half interarticular length (IAL) (Lazenby, 1994). Dorsopalmar (DP) and mediolateral (ML) axes were located with reference to landmarks of the dorsal and medial surfaces (detailed in Fig. 1) and marked with an indelible ink pen, after which an approximately 2 cm portion spanning the midshaft was removed, cleaned, and embedded in a clear epoxy resin. Plane parallel sections were cut at midshaft on a diamond slow-speed saw, oriented with respect to the DP and ML axes, and taped to a record sheet preprinted with a 10 mm scale, with the proximal surface up. Each section with accompanying scale was then scanned at 400 pixels per inch with 400% magnification and stored on disk. These digital images were subsequently edited in the program Photoshop® to highlight the endosteal and periosteal margins. In order to eliminate subconscious bias for or against any of the aforementioned hypotheses, this editing was done in batch mode, by side and ID number, without reference to age or sex (thus, in the case of paired metacarpals, editing of one side was completed 2 or more weeks prior to editing of the alternate side). Each edited image and scale was subsequently printed on a laser printer at 600 dpi with a further 250% magnification to expedite tracing using the program SLCOMM (Eschman, 1990). SLCOMM provides quantitative estimates of total area (TA) (mm^2), cortical area (CA) (mm^2), bending strength about the mediolateral (Ix) (mm^4), and dorsopalmar (Iy) (mm^4) axes, maximum (Imax) (mm^4) and minimum (Imin) (mm^4) bending strength, and rotation from the Ix (mediolateral) to Imin axes (Theta) (°). Parameters derived from these measurements include medullary area ($MA = TA - CA$, mm^2), percent cortical area (in this case calculated as CA/TA * 100), torsional strength ($J = Imax + Imin$, or alternatively $Ix + Iy$, mm^4) and Imax/Imin, which provides an index of shape under which departures from unity indicate noncircularity.

Replicate images and measurements were made for 25 randomly selected sections. The percent mean difference between sets ranged from −0.22% for CA to −1.36% for Imin. The technical error of measurement (TEM) for these paired observations was also determined and ranged from 0.62 mm^2 for CA to 7.49 mm^4 for Imax. TEM is calculated as the square root of imprecision variance (Mueller and Martorell, 1988) and is interpretable as the standard deviation of measurement error; thus, replicate measures should fall within ± TEM 67% of the time.

Bone cross-sectional geometric variation is not independent of body and hence bone size (Ruff et al., 1993); thus, we expect that males will (generally) have absolutely larger skeletal dimensions than females, adults larger than children, and so on. From a

functional perspective, our interest is in whether there are also relative differences in size, for example, for a male and female of equal body size, does the former have larger bones? Size effects can be removed using appropriate ratios which incorporate least-squares regression coefficients within the model or alternatively by regression analysis to produce residuals (observed − expected values of Y at a given value of X) which can then be entered into subsequent analyses (Albrecht et al., 1993). Both approaches were employed in this study. In the former instance, intercept-adjusted ratios were derived for measured geometric variables (Theta excepted) following least-squares regression against interarticular length (IAL). (The appropriateness of this model was first confirmed graphically.) The resulting intercepts were entered into the equation ($Y/X + (a/b)$), where a is the Y intercept and b is the regression slope. Intercept-adjusted ratios are appropriate for noncurvilinear regressions in which $a \neq 0$ (Albrecht et al., 1993). A product-moment correlation of $r = 0$ between the adjusted Y values and X indicates removal of size effects. Values for r for adjusted Y on IAL range from −0.001 for Imin to 0.018 for TA, indicating minimal if any residual size effects remain following adjustment. Size-adjusted values for MA, J, and PCA were derived algebraically following adjustment of their constituent parameters. Least-squares residuals were also generated in the regression and saved to a datafile. Both sets of adjusted data gave nearly equivalent results in subsequent analyses, attesting to the efficacy of either approach. However, Albrecht et al. (1993) caution against the use of ratio adjustment since it may lead to a distortion of the resulting distribution which could compromise assumptions of ensuing statistical tests; consequently, only the regression residual analysis is reported here.

Patterns of variation were evaluated by correlation analysis and three-way factorial ANOVA (with grouping factors entered as age, sex, and side). Post-hoc comparisons were carried out using the Bonferroni/Dunn procedure, which provides adequate protection against Type I error irrespective of F-ratio significance (Zolman, 1993). All null hypotheses were tested against $\alpha = 0.05$. Statistical analyses were carried out using Statview 4.02.

RESULTS

Means ± SE for each geometric variable by sex, side, and nominal age are given in Table 1. Table 2 provides the product-moment correlation matrices for male and female data. The high positive correlation observed among some of the variables is not surprising (e.g., TA, CA, Ix, Imax, J, etc.) since these measures are neither statistically nor functionally independent. Measures of bending and torsional strength (I and J) are determined by the amount and distribution of bone tissue in a cross-section and thus will be directly influenced by area measures such as TA and CA. Directionality of specific correlations is consistent with expectations. For example, MA correlates positively with age while PCA correlates negatively with Age (as well as with TA). Both results are interpretable as a consequence of age-progressive endosteal resorption, which in the case of PCA diminishes the numerator, CA. There is a low but significant positive correlation for TA with age in the right male metacarpal, but this is absent in the left male metacarpal and in females; all the same, any increase in TA diminishes PCA.

Of interest are the apparent sexually dimorphic patterns for CA and age and for MA, age, and geometric measures of bending and torsional strength. In males, CA exhibits a small, insignificant negative correlation with age, while in females the negative correlation is significant. This can be attributed to a sex differential in relative change in TA and MA between the young and old adult cohorts (approximately +5 mm^2 and −4 mm^2 for male TA and MA and 1–2 mm^2 and 4–8 mm^2 for females). In males, MA is positively and significantly correlated with Ix, Iy, Imax, Imin, and J ($r = 0.39$–0.56), but this is not so in females, with the exception of right Ix and Imax ($r = -0.07$ to 0.29). The positive correlations are somewhat counterintuitive, as one would expect any diminution of bone mass to negatively impact measures such as I and J. However, endosteal bone contributes propor-

TABLE 1. Means (and sd) for geometric parameters of the second metacarpal by sex, side, and nominal age

	n	IAL (mm)	TA (mm^2)	CA (mm^2)	MA (mm^2)	PCA	Ix (mm^4)	Iy (mm^4)	Theta ((°)	Imax (mm^4)	Imin (mm^4)	Imax/ Imin	J (mm^4)
Male, left,	22	65.77	56.04	43.21	12.82	77.45	263.68	230.65	57.59	286.00	208.33	1.40	494.33
young		(4.14)	(9.21)	(6.49)	(3.93)	(4.78)	(79.17)	(75.36)	(18.87)	(83.45)	(67.34)	(0.20)	(147.55)
Male, left,	46	65.68	57.70	42.89	14.82	74.69	274.33	238.66	58.48	300.82	212.17	1.43	512.99
middle		(3.02)	(7.96)	(5.73)	(5.25)	(7.54)	(74.85)	(66.90)	(18.17)	(80.99)	(57.53)	(0.20)	(133.78)
Male, left,	36	66.35	60.25	43.06	17.19	71.48	300.44	251.24	58.62	328.41	223.26	1.48	551.67
old		(3.78)	(7.51)	(6.93)	(5.18)	(8.18)	(91.68)	(63.31)	(20.13)	(93.94)	(56.67)	(0.27)	(143.31)
Male,	23	66.09	57.88	43.80	14.08	76.16	287.47	244.10	118.53	311.09	220.53	1.42	531.62
right, young		(4.60)	(11.35)	(7.34)	(4.93)	(4.66)	(105.91)	(102.84)	(12.49)	(123.71)	(83.53)	(0.22)	(203.79)
Male,	46	65.43	60.82	45.59	15.23	75.26	313.65	259.20	117.95	340.40	232.46	1.48	572.85
right, middle		(3.13)	(7.66)	(5.82)	(5.30)	(7.12)	(83.38)	(63.55)	(16.89)	(87.08)	(59.12)	(0.24)	(138.65)
Male,	37	66.54	63.86	45.51	18.35	71.32	330.90	285.75	119.75	367.82	248.84	1.49	616.66
right, old		(2.99)	(7.24)	(7.19)	(5.57)	(8.55)	(88.47)	(73.17)	(26.20)	(90.68)	(59.74)	(0.20)	(144.06)
Female,	22	61.02	44.31	34.21	10.10	77.35	161.93	144.01	73.27	173.29	132.65	1.31	305.94
left, young		(4.30)	(5.34)	(4.07)	(2.88)	(4.98)	(43.03)	(38.44)	(42.29)	(43.70)	(32.07)	(0.18)	(72.61)
Female,	30	62.74	45.67	33.21	12.47	73.22	164.71	150.76	63.57	177.33	138.14	1.30	315.46
left, middle		(2.80)	(6.02)	(5.22)	(5.51)	(10.55)	(44.54)	(38.22)	(35.60)	(44.54)	(35.78)	(0.21)	(76.35)
Female,	19	61.83	45.09	28.37	16.72	63.07	154.18	131.17	73.96	162.81	122.53	1.33	285.34
left, old		(1.60)	(4.87)	(4.31)	(4.38)	(8.14)	(39.40)	(28.37)	(24.61)	(41.23)	(25.58)	(0.16)	(64.58)
Female, right,	24	61.05	46.39	36.14	10.25	78.05	177.17	158.71	111.55	189.64	146.25	1.30	335.88
young		(4.05)	(5.17)	(4.29)	(3.24)	(5.98)	(44.88)	(34.93)	(31.62)	(42.80)	(32.81)	(0.17)	(72.15)
Female, right,	32	62.81	48.47	34.80	13.67	72.33	187.29	165.89	121.08	203.80	150.10	1.37	353.18
middle		(3.01)	(5.96)	(5.61)	(6.46)	(11.28)	(50.02)	(38.83)	(33.62)	(49.08)	(35.40)	(0.23)	(78.67)
Female, right,	19	62.13	48.66	30.37	18.29	62.63	183.66	148.11	111.70	192.70	139.07	1.38	331.77
old		(2.18)	(4.81)	(4.14)	(4.93)	(8.13)	(41.14)	(25.26)	(22.44)	(41.13)	(23.73)	(0.17)	(62.31)

tionately less to bending and torsional rigidity, and even modest increases in TA can more than offset such decrements (Lazenby, 1990b). Although PCA is negatively correlated with age in both males and females, measures of bending and torsional rigidity are positively though not significantly correlated with age in males (but not in females). Thus, it appears that while males lose bone mass with increasing Age, they do not lose bone strength.

There is a curious pattern of correlation for the shape index, Imax/Imin. In both males and females and left and right bones, Imax/Imin is significantly and positively correlated with Ix and Imax and negatively correlated with both Iy and Imin (the latter significant only for the male right metacarpal). This suggests that increases in bending strength about the mediolateral (Ix) and Imax axes are associated with increasing noncircularity. This result is interpretable by considering that, for both male and female left metacarpals, Theta falls in the range of approximately 60–70°, while on the right side it ranges from approximately 110–120° in both sexes. These values orient the Imin axis (i.e., direction of greatest bending rigidity) between the lateral-dorsal and medial-palmar anatomical axes, though somewhat closer to the dorsal-palmar plane and at some distance from the mediolateral axis (Fig. 2). Thus, if Imax increases as a result of preferential bone deposition at the periosteal surface in the region bisected by the Imin axis, the result will be a noncircular section with larger values for both Imax and Ix and relatively smaller values for Iy and Imin.

Patterns observed in the correlation analysis become more evident in the ANOVA (Table 3). Sex was a significant factor for all variables except MA and Theta, with males having larger values than females (Table 1). Side was a significant main effect for all variables except MA and PCA (right side > left) and was the only factor influencing Theta.

As a main effect, age was significant only for CA, MA, and PCA, although several first-order sex × age interactions were significant. (Neither the first-order interaction

TABLE 2. Product-moment correlation coefficients[1]

	Age	TA	CA	MA	Ix	Iy	Theta	Imax	Imin	J	Imax/Imin	PCA
Males												
Age		.19*	−.05	.33*	.06	.19	.10	.13	.11	.12	.03	−.33*
TA	.15		.73*	.64*	.90*	.91*	.07	.93*	.94*	.97*	.06	−.64*
CA	−.08	.71*		−.06	.82*	.73*	−.02	.81*	.78*	.83*	.12	.06
MA	.30*	.69*	−.02		.39*	.51*	.15	.44*	.49*	.48*	−.05	−1.0*
Ix	.10	.91*	.77*	.49*		.73*	−.15	.96*	.82*	.94*	.27*	−.39*
Iy	.11	.90*	.72*	.54*	.71*		.31*	.84*	.93*	.92*	−.08	−.51*
Theta	−.03	.05	.08	−.01	.33*	−.27*		.07	.05	.07	.02	−.15
Imax	.12	.93*	.79*	.51*	.96*	.82*	.10		.83*	.97*	.34*	−.44*
Imin	.08	.93*	.75*	.56*	.81*	.92*	.02	.81*		.94*	−.22*	−.49*
J	.11	.98*	.81*	.56*	.94*	.90*	.07	.97*	.93*		.12	−.48*
Imax/Imin	.07	.12	.17	−.01	.34*	−.05	.13	.41*	−.18	.18		.05
PCA	−.30*	−.69*	.02	−1.0*	−.49*	−.54*	.01	−.51*	−.56*	−.56*	.01	
Females												
Age		.08	−.49*	.56*	−.05	−.19	.00	−.08	−.18	−.12	.19	−.56*
TA	.02		.50*	.51*	.91*	.82*	.09	.92*	.87*	.94*	.20	−.51*
CA	−.44*	.60*		−.49*	.63*	.76*	−.04	.68*	.76*	.74*	−.02	.49*
MA	.53*	.43*	−.47*		.29*	.08	−.05	.25*	.12	.21	.22	−1.0
Ix	−.11	.91*	.72*	.19		.73*	.19	.97*	.81*	.94*	.40*	−.29*
Iy	−.17	.86*	.78*	.07	.76*		.11	.83*	.96*	.92*	−.13	−.08
Theta	−.03	.10	.06	.04	.19	.01		−.09	.00	−.06	−.20	.05
Imax	−.13	.92*	.75*	.17	.97*	.86*	.11		.84*	.97*	.38*	−.25*
Imin	−.16	.89*	.80*	.09	.83*	.96*	.11	.86*		.94*	−.16	−.13
J	−.14	.94*	.80*	.14	.95*	.93*	.11	.98*	.95*		.17	−.21
Imax/Imin	.02	.25*	.06	.20	.42*	.00	.06	.43*	−.08	.23*		−.22
PCA	−.53*	−.43*	.47*	−1.0	−.19	−.07	−.04	−.17	−.09	−.14	−.20	

[1] For each sex, lower matrix = left metacarpal and top matrix = right metacarpal.
* Significant at $P \leq 0.05$.

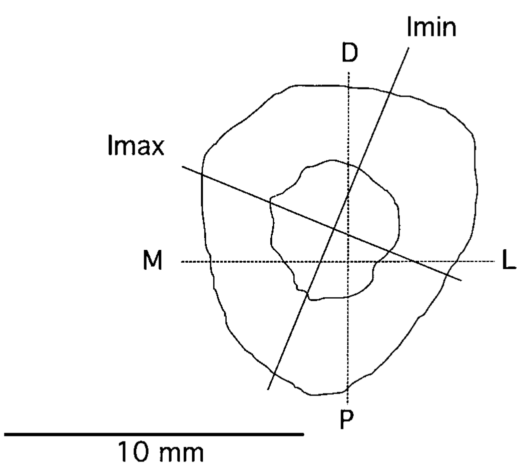

Fig. 2. Depiction of a cross-section from the left metacarpal midshaft from a 45-year-old male showing anatomical (dashed) and geometric (solid) axes of bending. The latter are translated to pass through the section centroid, which denotes the point at which compressive, tensile, and torsional strains are zero. Note the dorsolateral/mediopalmar direction of greatest bending strength, denoted by the Imin axis. D, dorsal; P, palmar; M, medial; L, lateral.

age × side nor the second order interaction sex × age × side was significant in any instance, and the sex × side interaction was significant solely for Theta as a result of the strong main effect for side.) The sex × age interaction appears to be primarily a function of sex; that is, age has an effect depending upon whether the subject is male or female. Again, this can be traced to the absence of an increase in TA with age in females and its presence in the male right metacarpal (Fig. 3). While males exhibit absolutely larger geometric properties than females, young and middle adult males have relatively lower bone mass as reflected by PCA (Fig. 4). The precipitous decline in PCA for old adult females is a result of a much greater rate of bone loss, a pattern also observed by Plato and Purifoy (1982). Although older individuals have larger values for Imax/Imin than younger (Bonferroni/Dunn $P = 0.0063$), sex was identified as the only main effect with a significant influence on the shape index, Imax/Imin. Male metacarpals were found to be less circular than females in both sides and at all ages (approximately 1.45 in males and approximately 1.33 in females) (Table 1).

The Bonferroni/Dunn post-hoc tests (not tabulated) generally emulate the ANOVA results with regard to the dichotomous cat-

TABLE 3. F ratios for three-way ANOVA

	TA	CA	MA	PCA	Ix	Iy	Theta	Imax	Imin	Imax/Imin	J
Sex	78.01*	102.58*	0.97	0.97	74.17*	72.77*	1.97	86.74*	66.57*	13.32*	85.45*
Age	2.41	9.55*	30.60*	30.60*	0.48	0.02	0.03	0.60	0.01	1.62	0.20
Side	11.90*	9.81*	2.22	2.72	10.53*	7.75*	334.56*	11.16*	7.99*	1.85	10.72*
Sex × age	2.74	7.90*	2.72	2.22	3.26*	4.10*	.005	4.24*	3.09*	0.20	4.10*
Sex × side	0.00	0.01	0.00	0.00	0.37	0.37	7.77*	0.48	0.28	0.05	0.43
Age × side	0.37	0.34	0.11	0.11	0.33	0.22	1.26	0.34	0.15	0.54	0.27
Sex × age × side	0.08	0.58	0.21	0.21	0.17	0.25	1.74	0.07	0.20	0.17	0.12

* Significant at $P < 0.05$.

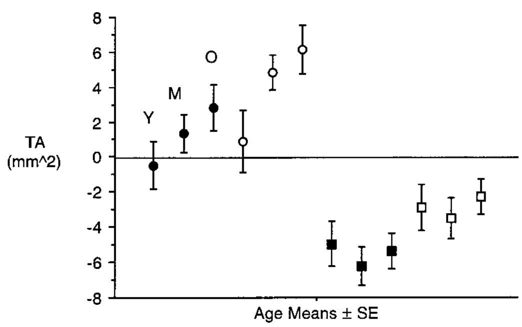

Fig. 3. Plot of means ± SE for total area (TA) residuals by age group for male (circles) and female (squares) metacarpals. Closed symbols denote the left side, open symbols the right side. M, middle adult; O, old adult; Y, young adult.

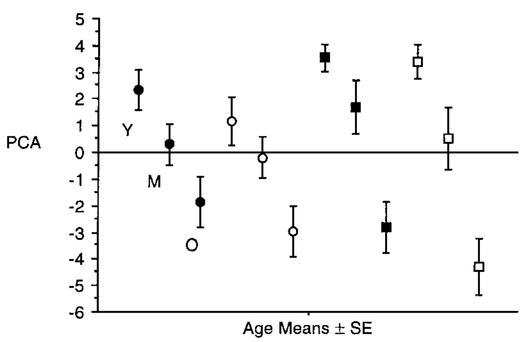

Fig. 4. Plot of means ± SE for percent cortical area (PCA) residuals by age group for male (circles) and female (squares) metacarpals. Closed symbols denote the left side, open symbols the right side. M, middle adult; O, old adult; Y, young adult.

egories of sex and side. With regard to age, the cross-sectional area measures MA and PCA were found to be significant for all contrasts (young vs. middle, young vs. old, and middle vs. old), while for TA, Imax, and Imax/Imin only the young/old contrast achieved significance.

DISCUSSION AND CONCLUSIONS

This study tested three null hypotheses specifying a lack of age, sex, or side effect in second metacarpal geometric variation. There is a general impression, primarily originating in the radiogrammetric literature, that older individuals have lower bone mass than younger ones and that males have more cortical bone than females at all ages (e.g., Plato and Purifoy, 1982; Maggio et al., 1997). The evaluation of limb dominance from metacarpal cortical bone size has been somewhat more equivocal. Garn et al. (1976) found the right side to be larger irrespective of handedness, as did Plato and Norris (1980), although in the latter study left-hand dominance rendered the size difference nonsignificant. More recently, Roy et al. (1994) validated the relationship of lateral hand dominance and bone asymmetry, with significantly larger metacarpal dimensions—including medullary area—associated with the dominant limb, and as a consequence argued that environmental rather than genetic factors had the most profound influence on mechanical adaptation in cortical bone.

The present study confirms these impressions with regard to some but not all aspects of the structural properties of the second metacarpal midshaft. For example, males do have larger (size-adjusted) cortical bone mass than females, though this does not extend to medullary area. This is perhaps paradoxical, since in the St. Thomas data males in fact have larger medullary areas at all ages (Table 1). However, with aging there is a 29% increase in medullary area in the male left metacarpal and 26% on the right side, while in females the corresponding figures are 49% and 56%, resulting in increasingly

similar MA values for the two sexes with age.

Similarly, right metacarpal geometric parameters are larger than those observed on the left side, though this study, using an archaeological sample, does not control for hand preference. Interestingly, the proportion of bones among the paired metacarpals in this sample (n = 158 individuals) that have larger values on the left side ranges from 14.6% for TA to 25.9% for CA (for the derived variable medullary area, the figure is 41.1%). Left-hand dominance in the majority of human populations typically falls in the range of 5–10% (Plato et al., 1984b; Porac, 1993), though some have suggested a natural value of 34% (Bryngelson, cited in Napier, 1993), with the lower values observed incorporating right dominance resulting from a combination of biological and cultural factors (e.g., teachers and parents admonishing children demonstrating a left-hand preference). One might expect proportions in this range for measures of bone size if, as Roy et al. (1994) suggest, environment (i.e., usual mechanical loading, in this instance) is the major determinant for bone size. The larger proportions for greater size in the left second metacarpal observed here suggests that 1) either the St. Thomas sample is more in keeping with the magnitude of left-handedness Bryngelson suggests as being normal (i.e., the aforementioned cultural biases were less selective for right-handedness), or 2) factors other than hand dominance enter into the determination of bone size. With regard to the latter, strenuous activities less frequently performed with the nondominant (in this case, left) limb could constitute such a factor. Experimental studies with in vivo models show that both peak strain magnitude and strain distribution associated with particular loading scenarios determine localized bone gain and loss (Lanyon, 1993) and that relatively few, although large, applied loads will elicit an osteogenic response. The occupational histories of individuals in this sample is not known. Among males, heavy labour (woodsman, blacksmith) would involve two-handed power grips which one might reasonably suspect could generate large dynamic loading in the left limb, though whether this would be greater than that experienced by the right side remains to be demonstrated empirically. Domestic activities such as collecting and carrying well water, gardening, and other heavy housework may involve greater left-handed idiosyncratic preferences based on convenience and/or comfort, even though an individual might use the right hand form the majority of tasks (e.g., writing, cutting).

Contrary to the pattern seen for the main effects of sex and side, age does not appear to have a significant influence independent of sex, with major exceptions for cortical area, medullary area, and percent cortical area. Parameters of bending strength such as Ix or Imax are strongly determined by the amount of bone within the cross-section and its distribution relative to the axis of bending, with cortex further removed from the axis of bending contributing disproportionately to strength (Lazenby, 1990b), and they will thus will be most sensitive to changes in total area. In their study of BLSA males, Plato and Norris (1980) found no significant increase with age across 7+ decades in total diameter, as did Plato and Purifoy (1982) in BLSA males and females and more recently Maggio et al. (1995, 1997) for individuals beyond age 65 in their clinical studies of aging bone loss. Plato and Norris (1980) argued that the absence of age changes in total diameter indicated that bone size was determined by physical forces prior to attainment of adulthood. Such an explanation is at odds with currently accepted models of functional adaptation and dynamic modeling in cortical bone (Martin and Burr, 1989; Lazenby, 1992) and the recognition that periosteal apposition is an age-progressive and continuous process throughout life (Lazenby, 1990a). However, some experimental work with avian models (Rubin et al., 1992) indicates that the older skeleton has a less labile osteogenic response; that is, an environmental cue sufficient to initiate bone formation in younger animals is not recognized in the older group. This suggests an age-related shift in the set point for bone formation toward requiring a stimulus of greater magnitude. This could account for the observation in the present study that age and total area are significantly corre-

lated only in the male right metacarpal, which, among the four metacarpals distributed by sex and side, one might assume receives the largest mechanical loading. As a cautionary note, however, it must be borne in mind that a statistically insignificant increase in total area with age does not by necessity translate as functional insignificance (Lazenby, 1990a), since small increments of new periosteal bone can preserve bending strength in the face of comparatively large volumes of endosteal bone loss (Lazenby, 1990b). Hence, the absence of a significant main effect for age and TA in the ANOVA leaves unanswered the question of whether individuals in this sample were unable to maintain bone strength as they aged. A further complicating factor is context: strength must be assessed against the kinds and magnitude of loads applied, and one might reasonably surmise that these would be both different and lower in older as compared to younger individuals.

Values for Imax/Imin indicate significant departures from an hypothesized mean of 1.0 expected under the hypothesis of a circular midshaft cross-section ($P \leq 0.001$ for all sex $\times$ side comparisons). This result mirrors that of an earlier study investigating this question in the subsample of known individuals from the St. Thomas collection (Lazenby, 1995), though that study employed biplanar radiogrammetric data rather than data obtained from direct measurement as in the present investigation. It is in stark contradiction with numerous statements in the radiogrammetric literature which require the invocation of the circular model in the derivation of measures such as the metacarpal index (Barnett and Nordin, 1960), percent cortical area (Garn, 1970) or combined cortical thickness (e.g., Plato and Norris, 1980). Garn (1970: 7) specifically addresses the question of cylindrical models, noting that it “has been verified experimentally for the 2nd metacarpal, using dried bones before and after sectioning,” though unfortunately no reference to that study is given.

The functional interpretation of a circular cross-section is that of a bone subjected to bending loads of equal magnitude, frequency, and duration applied uniformly from all directions or alternatively a loading scenario that excludes bending and is purely axial (Lazenby, 1990b; Martin and Burr, 1989). These are unrealistic scenarios for any skeletal element. Study of hand-wrist morphology from an evolutionary perspective suggests that large compressive axial *and* bending loads characterize the second metacarpal during manipulative and tool-manufacturing behaviours (Marzke 1997; Marzke and Shackley, 1986; Marzke et al., 1992). In the present study, the axis of greatest bending rigidity at midshaft was oriented in an approximately dorsolateral/mediopalmar plane. Most effort in past functional studies has emphasized variation in joint surfaces rather than bone shafts. However, Marzke (1997) notes that asymmetries in both proximal and distal joint surfaces accommodate pronation of the human second metacarpal in a variety of grips, maximizing both joint stability as well as force transmission across the carpometacarpal articulation with the trapezium and trapezoid. Pronation of the second metacarpal (and extending to supination of the fifth metacarpal) defines the distal palmar arch, and bending forces associated with grasping or manipulating objects held against the palm might be expected to orient at right angles to the arch (i.e., in a mediopalmar to dorsolateral plane). While speculative, this is a not unreasonable model pending more detailed study of deformation in bones of the hand. It also suggests predictions regarding midshaft shape variation in metacarpals III–V (e.g., lateromedial rotation of the Imax and Imin axes conforming to the distal palmar arch). Such predictions also engender both ontogenetic and phylogenetic hypotheses regarding intra- and interspecific developmental timing of this pattern and associated behaviours. Within the context of the present study, the origin of the significant difference in noncircularity between males and females remains to be explained, though the most parsimonious account would invoke qualitative differences in hand use (i.e., different grips associated with gender-specific behaviours). Again (as noted previously), the occupations of the individuals in this sample are unknown. It might not be unreasonable to suppose that women were employed by and large in a domestic context. If

household activities provided more diversity in mechanical loading than those of men employed outside of the home, a more circular cross-sectional shape in female bones would be expected. It should be emphasized, however, that the metacarpal midshaft of both males and females in this sample is noncircular in shape (see Table 1), consistent with a mechanical environment of bending and torsion.

This investigation provides the first normative data for directly measured geometric variation at the second metacarpal midshaft, an anatomical locus that has been the subject of much study in the past. Correlation analysis and three-way ANOVA confirms and extends our understanding of patterns of age, sex, and side differences. Males have absolutely but not relatively larger bones at all ages, while females lose more bone mass with aging. Asymmetry is marked and generally favours the right side, though not to the degree suggested by studies of handedness in modern human populations. A large proportion of both males and females in this study exhibits greater structural strength properties on the left side. Finally, an assumption of previous radiogrammetric studies that the metacarpal midshaft cross-section can be modelled as a circle is unwarranted, as both male and female shape ratios depart significantly from a hypothesized value of 1.0. This noncircularity reflects a deviation of the axis of greatest bending rigidity oriented in the dorsolateral/mediopalmar plane, which may reflect a primary axis of bending in the human second metacarpal consistent with both precision and power grips and formation of the distal palmar arch.

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